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A NEW CLASS OF HIGH-MASS X-RAY BINARIES: IMPLICATIONS FOR CORE COLLAPSE AND NEUTRON-STAR RECOIL

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ABSTRACT

We investigate an interesting new class of high-mass X-ray binaries (HMXBs) with long orbital periods ($P_{\rm orb} > 30\,{\rm d}$) and low eccentricities ($e \lesssim 0.2$). The orbital parameters suggest that the neutron stars in these systems did not receive a large impulse, or "kick," at the time of formation. After considering the statistical significance of these new binaries, we develop a self-consistent phenomenological picture wherein the neutron stars born in the observed wide HMXBs receive only a small kick ($\lesssim 50\,{\rm km\,s^{-1}}$), while neutron stars born in isolation, in the majority of low-mass X-ray binaries, or in many of the well-known HMXBs with $P_{\rm orb} \lesssim 30\,{\rm d}$ receive the conventional large kicks, with a mean speed of $\sim 300\,{\rm km\,s^{-1}}$. Assuming that this basic scenario is correct, we discuss a physical process that lends support to our hypothesis, whereby the magnitude of the natal kick to a neutron star born in a binary system depends on the rotation rate of its immediate progenitor following mass transfer — the core of the initially more massive star in the binary. Specifically, the model predicts that rapidly rotating pre-collapse cores produce NSs with relatively small kicks, and vice versa for slowly rotating cores. If the envelope of the NS progenitor is removed before it has become deeply convective, then the exposed core is likely to be a rapid rotator. However, if the progenitor becomes highly evolved prior to mass transfer, then a strong magnetic torque, generated by differential rotation between the core and the convective envelope, may cause the core to spin down to the very slow rotation rate of the envelope. Our model, if basically correct, has important implications for the dynamics of stellar core collapse, the retention of neutron stars in globular clusters, and the formation of double neutron star systems in the Galaxy.

Subject headings: stars: neutron — supernovae: general — X-rays: stars

1. INTRODUCTION

It has become fashionable in recent years to suppose that the majority of neutron stars (NSs) are born with speeds in excess of $\sim 100 - 200\,{\rm km\,s^{-1}}$, presumably as a result of some asymmetry in the core collapse or the subsequent supernova (SN) explosion of the NS progenitor. The strongest support for this notion comes from the high speeds inferred for the ~ 100 Galactic pulsars with well-measured interferometric proper motions (Harrison, Lyne, & Anderson 1993). Mean speeds for these pulsars of $\gtrsim 300\,{\rm km\,s^{-1}}$ have been estimated by a number of authors (e.g., Lyne & Lorimer 1994; Hansen & Phinney 1997; Cordes & Chernoff 1998; Arzoumanian, Chernoff, & Cordes 2001). Various classes of binary systems containing NSs also show strong evidence for substantial natal "kick" velocities, based upon their present orbital parameters, their systemic speeds, and/or their height above the Galactic plane (e.g., Brandt & Podsiadlowski 1995; Verbunt & van den Heuvel 1995; Johnston 1996; van den Heuvel et al. 2000).

Very large uncertainties, both observational and theoretical, still pervade studies of the underlying distribution in NS natal kick speeds. Complications include the fairly small sample of pulsars with proper-motion measurements, questionable dispersion-measure distances, serious observational selection effects, and uncertainties regarding the formation of NSs and their dynamical evolution in the Galaxy. Fortunately, the sample of pulsars with reliable proper motions is growing (see McGary et al. 2001), as is the number of pulsars with accurate parallax distances (e.g., Toscano et al. 1999; Brisken et al. 2000).

The most popular models for NS kicks involve a momentum impulse delivered around the time of the core collapse that produced the NS. Mechanisms in this class include purely hydrodynamical processes, as well as primarily neutrino-driven kicks (see Lai 2000 for a review). In either case, some process must be responsible for breaking spherical symmetry during core collapse, such as a combination of Rayleigh-Taylor instabilities and neutrino-induced convection (e.g., Janka & Müller 1994; Fryer & Heger 2000). A fundamentally different mechanism for producing significant NS velocities was proposed by Harrison & Tademaru (1975), whereby the NS is accelerated

after the core-collapse event as a result of asymmetric electromagnetic (EM) dipole radiation — the so-called EM "rocket" effect. This process is distinctly non-impulsive.

A theoretical determination of the emergent velocity distribution associated with each kick mechanism is extremely difficult and would require an ensemble of very detailed three-dimensional hydrodynamical simulations (with the exception of the EM "rocket" mechanism). Furthermore, it is unlikely that a single process accounts for the full range of NS velocities. For instance, it is plausible that the dominant kick mechanism and the magnitude of the kick depend at least somewhat on the evolutionary history of the NS progenitor. In this paper, we explore a possible linkage between the kick magnitude and the evolution of the NS progenitor in a binary system. This work was inspired by a new observed sub-class of high-mass X-ray binaries (HMXBs).

Previously, significant eccentricities of $e \sim 0.3 - 0.5$ seemed to be the general rule among HMXBs with $P_{\rm orb} \sim 20 - 100\,{\rm d}$ (see Bildsten et al. 1997), which is presumably the result of a substantial NS kick (e.g., Brandt & Podsiadlowski 1995; Verbunt & van den Heuvel 1995; van den Heuvel et al. 2000). By contrast, the new class of HMXBs are clearly distinguished by their low eccentricities of $e \lesssim 0.2$ and long orbital periods of $P_{\rm orb} \sim 30-250\,{\rm d}$, which indicate that tidal circularization should not have played a significant role if the massive stellar component is not very evolved. Eccentricities of this magnitude are roughly consistent with the dynamical effect of mass loss alone in the SN explosion, although relatively small kick speeds of $\lesssim 50\,{\rm km\,s^{-1}}$ cannot be ruled out on statistical grounds.

There are currently six candidates for the new class of HMXBs. This is a substantial number, given the difficulties associated with detecting these binaries and measuring their orbits, and the fact that there are only ~ 20 HMXBs with measured orbital parameters. We suggest that the observed wide, nearly circular HMXBs are representative of a much larger intrinsic population, and that the NSs in these systems received only a small kick ($\lesssim 50\,{\rm km\,s^{-1}}$). We further speculate that the magnitude of the kick is correlated with the evolutionary history of the binary system, before the formation of the NS. Specifically, we propose that the kick speed depends on the rotation rate of the core of the NS progenitor following a phase of mass transfer, wherein the hydrogen-rich envelope of the star is removed. The sense is that slowly rotating cores produce NSs with the conventional large kicks, while the collapse of rapidly rotating cores are accompanied by relatively small natal kicks. If our basic picture is correct, there may be important implications for magnetic field evolution and core collapse in massive stars, the retention of NSs in globular clusters, and the birthrate of double NS binaries in the Galaxy.

In § 2, we discuss the observed characteristics of the new class of wide, low-eccentricity HMXBs. A brief theoretical overview of the formation, evolution, and population synthesis of massive binaries is given in § 3. Using a combination of theoretical and observational arguments, we claim in § 4 that mean kick speeds of $\gtrsim 200 - 300\,{\rm km\,s^{-1}}$ are not consistent with the numbers and properties of the members of the new observed class of HMXBs, and that considerably smaller kicks of $\lesssim 50\,{\rm km\,s^{-1}}$ are probably required. We develop in § 5 a phenomenological picture that accounts for the new HMXBs, and which is consistent with what is known about the Galactic NS populations. We lend some credence to this basic picture by suggesting a plausible physical scenario in § 6 that naturally relates the rotation rate of the pre-collapse core (NS progenitor) and the evolutionary history of its host binary system. Finally, we investigate in § 7 a number of further implications of the new class of HMXBs and our associated model. Our main points are summarized in § 8.

2. A NEW CLASS OF HIGH-MASS X-RAY BINARIES

A HMXB consists of a NS, which often appears as an X-ray pulsar, and a massive stellar companion. Of the ~ 130 known HMXBs (see Liu, van Paradijs, & van den Heuvel 2000), ~ 20 have reasonably well-measured orbital elements (see Bildsten et al. 1997 for a somewhat dated list). In all but one case (γ Cas; Harmanec et al. 2000), the parameters were determined from the timing of the X-ray pulsar.

Two classes of HMXBs, distinguished by their orbital parameters, are apparent in Table 3 of Bildsten et al. (1997): (i) systems with $P_{\rm orb} \lesssim 10\,{\rm d}$ and $e \lesssim 0.1$, and (ii) moderately wide, eccentric binaries with $P_{\rm orb} \sim 20-100\,{\rm d}$ and $e \sim 0.3-0.5$. A new third class of HMXBs has recently emerged. These systems are distinguished from the well-known HMXBs by their wide orbits (all have $P_{\rm orb} > 30\,{\rm d}$) and fairly low eccentricities ($e \lesssim 0.2$). Table 1 lists the names and orbital parameters of these interesting binaries, and below we give a brief synopsis of relevant observational information for each system. For two of the binary X-ray pulsars discussed below (XTE J1543–569 and 2S 1553–542), the optical counterpart has not been identified. In these cases, we should remain open to the possibility that the companion may have evolved beyond the main sequence and is filling a significant fraction of its Roche lobe, thus explaining the low eccentricities.

2.1. *Observational Information for Each Binary*

2.1.1. *X Per/4U 0352+309*

The X-ray counterpart to the classical Be (or possibly Oe) star X Per, 4U 0352+309, exhibits pulsations with a period of $\sim 837\,{\rm s}$. Variations in the pulse period strongly suggest that the X-ray source is an accreting NS. The X-ray pulsar was observed by Delgado-Martí et al. (2001) over an interval of nearly 600 days with the *Rossi X-ray Timing Explorer* (*RXTE*). These observations have revealed the orbital period of the system, $P_{\rm orb} = 250.3 \pm 0.6\,{\rm d}$, and the orbital eccentricity, $e = 0.111 \pm 0.018$.

Estimates of the distance to X Per range from $700 \pm 300\,{\rm pc}$ to $1.3 \pm 0.4\,{\rm pc}$ (see Delgado-Martí et al. 2001 and references therein). It is then especially interesting to note that X Per lies at a Galactic latitude of approximately $-17°$. For an assumed distance of $\sim 1\,{\rm kpc}$, this latitude places X Per at a height of $\sim 300\,{\rm pc}$ above the Galactic plane, which is much larger than the scaleheight of early-type stars in the Galactic disk. This large height may be explained by the systemic impulse received due to the mass loss and kick associated with the formation of the NS. However, the magnitude of the kick would have to be quite

TABLE 2
ORBITAL PARAMETERS FOR NEARLY CIRCULAR HIGH-MASS X-RAY BINARIES.

Object	$P_{\rm orb}$ (days)	e	$f_{\rm X}(M)(M_\odot)$[a]	References
X Per/4U 0352+30	249.90 ± 0.50	0.111 ± 0.018	1.61 ± 0.06	1
γ Cas/MX 0053+604[b]...	203.59 ± 0.29	0.260 ± 0.035	...	2
GS 0834–430	105.80 ± 0.40	< 0.17	0.2 ± 0.3	3
XTE J1543–568	75.56 ± 0.25	< 0.03	8.2 ± 0.5	4
KS 1947+30	41 ± 1	< 0.15	< 5	5,6
2S 1553–542	30.60 ± 2.20	< 0.09	5.0 ± 2.1	7

[a]Mass function from X-ray timing.

[b]Orbital parameters determined from the optical light curve.

References. — (1) Delgado-Martí et al. 2001; (2) Harmanec et al. 2000; (3) Wilson et al. 1997; (4) in 't Zand, Corbet, & Marshall 2001; (5) Chakrabarty et al. 1995; (6) Galloway et al. 2001, in preparation; (7) Kelley, Rappaport, & Ayasli 1983

large, and the near circularity of the orbit would make the X Per system a very unlikely object. A far simpler and more reasonable hypothesis is that the binary was, in fact, born in an OB association within the Gould Belt (e.g., Torra, Fernández, & Figueras 2000), a disk-like structure with a radial extent of $\gtrsim 500$ pc, inclined by $\sim 20°$ to the Galactic plane. It is thought that the associations comprising the Gould Belt account for roughly 60% of the O and B stars within ~ 500 pc from the Sun.

2.1.2. *γ Cas/MX 0053+604*

It has long been suspected that γ Cas, the first-known Be star (Secchi 1867), is a member of a binary system; however, the orbit has defied detection at both X-ray and optical wavelengths until very recently. Harmanec et al. (2000) have measured the orbit of the γ Cas system using optical spectroscopy. Periodic shifts in Hα and He I line features were attributed to the orbital motion of the Be star. The Hα measurements yielded the orbital parameters $P_{\rm orb} = 203.59 \pm 0.29$ d and $e = 0.26 \pm 0.035$. The optical mass function implies that the unseen companion has a mass of $\sim 1\,M_\odot$, consistent with a massive white dwarf or a NS.

There is still debate regarding the nature of the X-ray counterpart to γ Cas, MX 0053+60. If the companion is indeed a compact object, it is not clear from the X-ray emission whether it is a NS or a white dwarf (e.g., no pulsations have been detected). However, if the system presently contains a white dwarf, we would expect the orbit to be circular as a result of an earlier episode of mass transfer. On these grounds, the NS hypothesis is compelling, since the SN that accompanied the formation of the NS could have easily perturbed the orbit to yield the observed eccentricity. Smith, Robinson, & Corbet (1998; see also Robinson & Smith 2000) argue against the hypothesis that the X-rays emanate from a compact object and favor a model where the X-ray emission is the result of magnetic activity on the stellar surface. Further observations are required to determine the origin of the X-rays and the nature of the companion to γ Cas.

2.1.3. *GS 0834–430*

Wilson et al. (1997) analyzed the data from seven outbursts of the transient X-ray pulsar GS 0834–430, observed with the BATSE instrument on board the *Compton Gamma Ray Observatory* (*CGRO*). Timing analysis of the 12.3 s X-ray pulsar revealed an orbital period of $P_{\rm orb} = 105.8 \pm 0.4$ d, but did not place very tight constraints on the eccentricity. According to Wilson et al. (1997), a likely value for the eccentricity is $e \lesssim 0.2$; larger values are permitted, but require a very small binary inclination. From the spin-up behavior of the X-ray pulsar, the estimated distance of the binary is $\gtrsim 4.5$ kpc. The optical counterpart to GS 0834–430 has been identified as a Be star by Israel et al. (2000)

2.1.4. *XTE J1543–569*

After a year-long monitoring campaign with *RXTE*, in 't Zand, Corbet, & Marshall (2001) have determined the orbital parameters of the X-ray pulsar XTE J1543–569. The system has an orbital period of $P_{\rm orb} = 75.56 \pm 0.25$ d and an eccentricity of $e < 0.03$ at the $2\,\sigma$ level. This eccentricity is surprisingly small if the massive companion to the NS is near the main sequence and thus is greatly underfilling its Roche lobe, even if we assume that the NS did not receive a kick. However, an optical counterpart has yet to be discovered, although the orbital and pulse periods place XTE J1543–569 amongst the confirmed Be/X-ray transients in the "Corbet" diagram (Corbet 1986; see also Bildsten et al. 1997).

It is interesting to note that the present eccentricity of XTE J1543–569 is not likely to be consistent with a vanishing NS kick. If we consider only mass loss in the SN explosion, the induced eccentricity for an initially circular orbit is $e = \Delta M/(M_b - \Delta M)$, where ΔM is the mass lost and M_b is the pre-SN mass of the binary (e.g., Blaauw 1961; Dewey & Cordes 1987). An eccentricity of ~ 0.03 is obtained if $\Delta M = 0.6\,M_\odot$, for a pre-collapse core mass of $2\,M_\odot$, and $M_b = 20\,M_\odot$, a somewhat high but not very unlikely mass. However, more typical values of ΔM and M_b are $1.6\,M_\odot$ and $15\,M_\odot$, respectively, which yield $e \sim 0.12$. In this case, a kick is required to "correct" the eccentricity to produce the smaller observed value, but the magnitude

and direction of the kick must be somewhat finely tuned. We suggest that possibly either the stellar companion to the X-ray source XTE J1543–569 is very massive or that the companion has evolved well beyond the main sequence and is filling a sizable fraction of its Roche lobe, so that tidal circularization accounts for the low eccentricity.

2.1.5. *KS 1947+30*

The transient X-ray source KS 1947+30 was first detected by the Kvant instrument on board the *Mir* space station (Borozdin et al. 1990). Later, in 1994, 18.7 s X-ray pulsations were detected by BATSE during an outburst that lasted 33 d (Chakrabarty 1995 and references therein). However, the $\sim 10\,\mathrm{deg}^2$ position resolution of BATSE was not sufficient to identify the X-ray pulsar as the Kvant source, and the pulsar was given the designation GRO J1948+32. Modulation of the pulse frequency during the 33 d outburst was suggestive of a binary orbit, but with less than one full orbital cycle of coverage. Preliminary estimates placed the orbital parameters in the ranges $35\,\mathrm{d} < P_{\rm orb} < 70\,\mathrm{d}$ and $e < 0.25$

A recent outburst has allowed KS 1947+30 to be "rediscovered" by the All Sky Monitor (ASM) on board *RXTE* (Galloway et al. 2001, in preparation). It was quickly realized that GRO J1948+32 and the old Kvant source are the same, and so the earlier designation, KS 1947+30, has been adopted. The X-ray pulsar has now been timed for ~ 5 orbits, and a precise orbital solution has been determined, with $P_{\rm orb} = 41.12 \pm 0.65\,\mathrm{d}$ and $e = 0.12 \pm 0.02$. Furthermore, the accurate position has led to the identification of an optical counterpart, probably an O/Be star (Negueruela, Marco, Speziali, & Israel 2000).

2.1.6. *2S 1553–542*

The transient X-ray pulsar 2S 1553–542 was first detected with the *SAS 3* satellite during the only known outburst of the source in 1975 (see Apparao et al. 1978). Kelley, Rappaport, & Ayasli (1983) analyzed data that spanned 20 d of the outburst and discovered regular variations in the 9.27 s pulse period that they attributed to a binary orbit. They determined that the system has an orbital period of $P_{\rm orb} = 30.6 \pm 2.2\,\mathrm{d}$ and an eccentricity of $e < 0.09$. The orbital parameters were not well constrained because the observations did not cover a full orbital cycle. Although no optical counterpart to 2S 1553–542 has been identified, the highly transient nature of the source is suggestive of an unevolved Be star companion (see Kelley, Rappaport, & Ayasli 1983 and references therein).

3. AN OVERVIEW OF MASSIVE BINARY POPULATION SYNTHESIS

From a theoretical point of view, the formation of a NS in a binary system involves three distinct evolutionary steps: (1) the formation of a primordial binary, where the initially more massive component (the primary) has a mass $\gtrsim 8\,M_\odot$, (2) a phase of mass transfer from the primary to the secondary[1] (the initially less massive component), which may be dynamically unstable, and (3) the subsequent SN explosion of the primary's hydrogen-exhausted core and the formation of the NS, where the disruptive influence of the SN may unbind the binary system. None of these steps is especially well understood, and so we encapsulate our lack of detailed knowledge in the form of a set of free parameters, some of which have values that are constrained by observations. In this paper, we present our results for one standard-model set of parameters. We have varied of number of the free parameters in our study and found that our main results and conclusions are unchanged. We now give a very brief overview of the elements of our Monte Carlo binary population synthesis code. A far more detailed discussion and an extensive set of references is provided in Pfahl, Rappaport, & Podsiadlowski (2001; hereafter, PRP).

The primary mass, M_1, is chosen from a power-law distribution, $p(M_1) \propto M_1^{-x}$, which is appropriate for massive stars (see Miller & Scalo 1979; Scalo 1986; Kroupa, Tout, & Gilmore 1993). For our standard model, we choose $x = 2.5$, where $x = 2.35$ corresponds to a Salpeter IMF (Salpeter 1955). An isolated star with solar metallicity will produce a NS if its mass is between ~ 8 and $30\,M_\odot$, where the upper limit is quite uncertain, but has little impact on our results. The secondary mass, M_2, is assumed to be correlated with the primary mass according to a distribution in mass ratios, $p(q) \propto q^y$, where $q \equiv M_2/M_1 < 1$. We adopt a flat distribution in mass ratios ($y = 0$) for our standard model.

We assume that the massive primordial binary is circular (see the remarks in PRP) and draw the orbital separation, a, from a distribution that is uniform in the logarithm of a (e.g., Abt & Levy 1978). The minimum value of a is determined from the constraint that neither star overflows its Roche lobe on the main sequence. The upper limit should be large, but is otherwise arbitrary, and its value does not significantly affect our results. In practice, we choose a maximum separation of 10^3 AU.

If the orbit of the primordial binary is sufficiently compact, the primary will grow to fill its Roche lobe, where the volume-equivalent radius of the Roche lobe about the primary is approximated by the formula due to Eggleton (1983):

$$\frac{R_{\rm L1}}{a} \equiv r_{\rm L1} = \frac{0.49}{0.6 + q^{2/3}\ln(1 + q^{-1/3})} \ . \qquad (1)$$

The evolutionary state of the primary when it fills its Roche lobe, in conjunction with the mass ratio of the components, is a good indicator of the physical character of the subsequent mass transfer and binary stellar evolution. It is common practice to distinguish among three evolutionary phases of the primary at the onset of mass transfer, following Kippenhahn & Weigert 1966 (see also Lauterborn 1970; Podsiadlowski, Joss, & Hsu 1992). Case A evolution corresponds to core hydrogen burning, Case B refers to the shell hydrogen-burning phase, but prior to central helium ignition, and case C evolution begins after helium has been depleted in the core. A large fraction of binaries will be sufficiently wide that the primary and secondary evolve essentially as isolated stars prior to the first SN. We refer to such detached configurations as case D. Cases A, B, C, and D comprise roughly 5%, 25%, 25%, and 45%,

[1] Hereafter, the term "secondary" will refer to the initially less massive star, whether or not the secondary has become the more massive component of the binary system as a result of mass accretion.

respectively, of the primordial binary population with our standard-model parameters.

It is particularly important to distinguish between mass transfer that is dynamically *stable* (proceeding on the nuclear or thermal timescale of the primary) and mass transfer that is dynamically *unstable* (proceeding on the dynamical timescale of the primary). Cases B and C are naturally divided into an *early* case (B_e or C_e), where the envelope of the primary is mostly radiative, and a *late* case (B_l or C_l), where the primary has a deep convective envelope. We assume that cases B_e and C_e mass transfer are stable if the mass ratio ($q = M_2/M_1$) is greater than some critical value, $q_{\rm crit}$, which we take to be 0.5 in our standard model. Cases B_l and C_l mass transfer are assumed to be dynamically unstable, regardless of the mass ratio. The reader is directed to PRP for further details.

During stable mass transfer, some fraction, β, of the material lost by the primary through the inner Lagrange point (L1) is accreted by the secondary. The excess material escapes the system with specific angular momentum $\alpha(GM_b a)^{1/2}$, where α is a dimensionless parameter and $M_b = M_1 + M_2$; both M_b and a take their instantaneous values during mass transfer. A reasonable analytic description of the orbital evolution is obtained when α and β (> 0) are held fixed (see Podsiadlowski, Joss, & Hsu 1992):

$$\frac{a'}{a} = \frac{M_b'}{M_b}\left(\frac{M_1'}{M_1}\right)^{C_1}\left(\frac{M_2'}{M_2}\right)^{C_2} \quad , \tag{2}$$

where

$$C_1 \equiv 2\alpha(1-\beta) - 2$$
$$C_2 \equiv -2\alpha\left(\frac{1}{\beta} - 1\right) - 2 \ . \tag{3}$$

Primes on the masses and semimajor axis indicate the values after some amount of mass has been transferred. For our standard model, we somewhat arbitrarily let $\beta = 0.75$, and we take $\alpha = 1.5$, a value characteristic of mass loss through the L2 point.

During stable mass transfer, the secondary will respond in one of two ways. If accretion occurs while the secondary is still on the main sequence, the secondary will generally be "rejuvenated." That is, the evolutionary clock of the secondary will be reset (though not precisely to the zero-age main sequence), and its subsequent evolution will be very similar to the evolution of an isolated star with a larger mass (Hellings 1983; Podsiadlowski, Joss, & Hsu 1992; Wellstein, Langer, & Braun 2001; but see also Braun & Langer 1995). On the other hand, if accretion occurs after the secondary has already exhausted hydrogen in its core, accretion increases the mass of the envelope, but does not affect the mass of the core. This changes the subsequent evolution of the secondary, since it is likely to spend the rest of its life as a blue rather than red supergiant (Podsiadlowski & Joss 1989). The latter accretion scenario has been proposed to explain the blue supergiant progenitor of SN 1987A. However, we do not consider this channel in the present study, since it accounts for only a few percent of massive primordial binaries.

Dynamically unstable mass transfer is accompanied by a common-envelope (CE) phase and a spiral-in of the secondary through the envelope of the primary. We use a standard, simple energy relation to determine the orbital separation following the spiral-in (e.g., Webbink 1984; Dewi & Tauris 2000):

$$\frac{a'}{a} = \frac{M_c M_2}{M_1}\left(M_2 + \frac{M_e}{2\eta_{\rm CE}\,\lambda\, r_{\rm L1}}\right)^{-1} \quad . \tag{4}$$

The constants λ and $\eta_{\rm CE}$ parameterize, respectively, the structure of the primary at the onset of Roche lobe overflow and the efficiency with which orbital binding energy is used to eject the CE. For our standard model, we choose $\eta_{\rm CE} = 1.0$ and $\lambda = 0.5$ (see Dewi & Tauris 2000). If the secondary fills its Roche lobe for the computed final orbital separation, we assume that the binary components have merged. For binaries that undergo unstable case B_e and C_e mass transfer, where $q < q_{\rm crit}$, we find that a merger occurs in nearly every instance.

In all cases where a stellar merger is avoided, we assume that the entire hydrogen-rich envelope of the primary is removed. By the time the primary reaches the base of the first giant branch (beginning of case B_l evolution) its core is well developed, with a mass given approximately by (e.g., Hurley, Pols, & Tout 2000)

$$M_c \simeq 0.1\, M_1^{1.35} \ , \tag{5}$$

where M_c and M_1 are in solar units. We assume that this is the mass of the helium core immediately following case B_e mass transfer as well, although it may be somewhat smaller, since mass transfer interrupts the evolution of the primary (Wellstein, Langer, & Braun 2001). For case C and D evolution, the mass of the core may be larger by $\sim 0.5 - 1\, M_\odot$ as a result of shell nuclear burning. If $M_c \lesssim 3\, M_\odot$ following case B mass transfer, the remaining helium star may grow to giant dimensions (Habets 1986b) upon central helium exhaustion and possibly fill its Roche lobe, initiating a phase of so-called case BB mass transfer (de Greve & de Loore 1977; Delgado & Thomas 1981; Habets 1986a).

At the end of the mass-transfer phase, the result should be a stellar merger or a binary consisting of the secondary and the core of the primary. Subsequently, the remaining nuclear fuel in the primary's core is consumed, leading to core collapse and a SN explosion. The post-SN orbital parameters are computed by taking into account the mass lost from the primary and the kick delivered to the newly-formed NS. In our simulations, we neglect the effect of the SN blast wave on the secondary. The mathematical formalism that we utilize to compute the post-SN orbital parameters is outlined in Appendix B of PRP.

The further evolution of the system depends on the orbital separation and the mass of the secondary following the SN, as well as the degree to which the secondary has been rejuvenated after it has accreted mass. If the secondary is of low or intermediate mass ($\lesssim 4\, M_\odot$) and the periastron separation of the post-SN orbit is not too large, the system will spend some time as a low- or intermediate-mass X-ray binary (e.g., Podsiadlowski, Rappaport, & Pfahl 2001) after the orbit circularizes and the secondary grows to fill its Roche lobe. If the secondary is massive, its strong stellar wind may allow the system to be detected as a HMXB. However, the extreme mass ratio guarantees that a CE and spiral-in will occur not long after the secondary fills its Roche lobe.

For this latter case where the secondary is massive, the final outcome of the spiral-in may be a merger, resulting

in the formation of a Thorne-Żytkow (1975, 1977) object, or the successful dispersal of the common envelope (if the orbital period after the first SN is $\gtrsim 100$ d; e.g., Taam, Bodenheimer, & Ostriker 1978). If collapse to a black hole, via "hypercritical" accretion (e.g., Chevalier 1993; Fryer, Benz, & Herant 1996; Brown, Lee, & Bethe 2000), and merger are avoided, the NS will emerge in a tight orbit with the hydrogen-exhausted core of the secondary. A double NS binary is then formed if the system remains bound following the supernova explosion of the secondary's core. In § 7.2, we discuss the implications of the new class of HMXBs for the formation of double NSs.

4. THE STATISTICAL SIGNIFICANCE OF THE NEW CLASS OF BINARIES

Before we begin to explore alternative models to explain the new class of HMXBs with wide orbits and small or moderate eccentricities, it is important that we provide some reasonable confirmation that this class is really a distinct population and does not fit within the conventional framework of massive binary population synthesis. It is, of course, possible that these systems are not dynamically significant (e.g., that their low eccentricities are result of tidal circularization), or that they represent the tail of a distribution and that some observational bias favors their detection.

4.1. *Tidal Circularization*

The high, persistent X-ray luminosities of the short-period HMXBs ($P_{\rm orb} \lesssim 10$ d) are probably maintained by a secondaries that are filling, or nearly filling, their Roche lobes. This hypothesis is supported by the ellipsoidal variations of the optical lightcurves a number of these sources, which indicate that the stellar companions are tidally distorted. Therefore, strong tidal interactions can easily explain the low eccentricities seen among the short-period HMXBs. However, it is extremely unlikely that tidal circularization has played a significant role in modifying the orbits of the new class of wide, nearly circular HMXBs.

Efficient tidal circularization requires that the star almost fills its Roche lobe and that there be an effective mechanism for damping the tide. These conditions are encapsulated by the cicularization timescale,

$$\tau_{\rm cir} \propto \tau_{\rm dis} \left(\frac{a}{R}\right)^8 , \qquad (6)$$

in the limit of weak tidal friction (e.g., Zahn 1977; Rieutord & Zahn 1997), where a is the semimajor axis of the orbit, R is the radius of the star, and $\tau_{\rm dis}$ is the timescale associated with viscous dissipation in the star. Radiative dissipation of the tidal luminosity is enormously inefficient in comparison to turbulent dissipation in a convection zone. As a result, the tidal coupling to the radiative envelope of a massive main-sequence star is much weaker than the coupling to the convective core (Zahn 1977). However, since the core only comprises $\sim 20\%$ of the radius of the star, the resulting circularization timescale is comparable to, or shorter than, the star's nuclear lifetime only when the star is very nearly filling its Roche lobe. This statement is supported by the near circularity ($e \lesssim 3\times10^{-3}$) of the orbits of SMC X-1, LMC X-4, and Cen X-3, which have periods less than 4 days (Bildsten et al. 1997; Levine, Rappaport, & Zojcheski 2000). However, tidal torques should have little effect on the orbit of a HMXB with $P_{\rm orb} \gtrsim 10$ d, as long as the secondary is not too evolved and the eccentricity is not so large that the tidal interaction is enhanced dramatically at periastron.

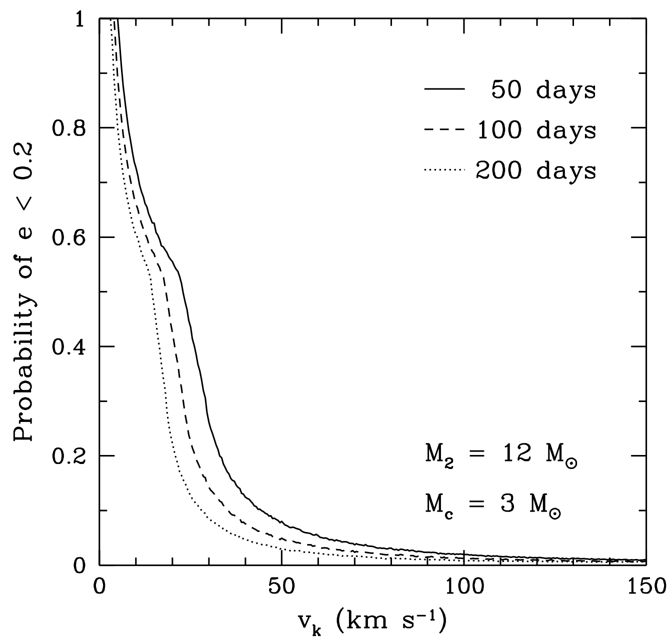

FIG. 1.— Probability that the post-SN eccentricity is < 0.2 for a helium star of mass 3 $M_\odot$ and a secondary of mass 12 $M_\odot$, for three different pre-SN orbital periods, as a function of the kick speed. The directions of the kicks are distributed isotropically.

4.2. *Observational Selection Effects*

There are currently six candidates for the class of wide, low-eccentricity HMXBs (Table 1), four of which have identified O or B optical counterparts. If we count all six candidates, then the new class of binaries accounts for roughly 30% of the HMXBs with measured orbital parameters. This fairly large fraction suggests that either these systems are preferentially selected for purely observational reasons or that their intrinsic population is actually quite large.

We should expect that an X-ray pulsar in a wide orbit with a low eccentricity is more difficult to detect and measure than if the orbital period is relatively short. There are two primary reasons for this. First, Bondi-Hoyle theory (Bondi & Hoyle 1944) predicts that the persistent luminosity of a wind-fed X-ray pulsar decreases with increasing orbital period, for a given rate of mass loss from the stellar companion. Therefore, very wide binaries have a small effective Galactic volume in which their orbits are readily measurable; e.g., for low-luminosity sources that resemble X Per/4U 0352+309, it would currently be difficult to determine orbits if the systems lie much beyond 1 kpc. Second, an accurate determination of the orbit from X-ray timing requires a series of observations that cover at least one full orbital cycle. If the orbital period is very long, this may not be feasible, especially given the transient behavior of many sources and the limited amounts of observing time. Transient sources, of which there are four in Table 1, may be very conspicuous during outburst, but because of their transient nature and possibly large

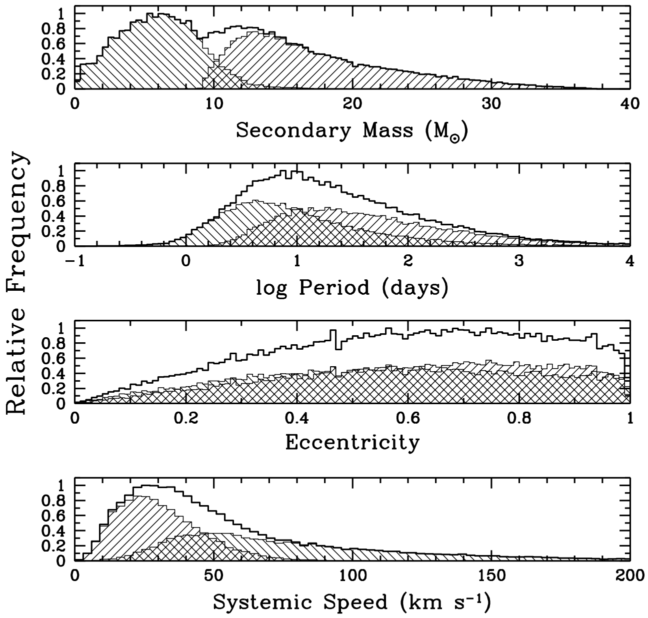

FIG. 2.— Distributions of binary parameters of systems that have undergone case B or C mass transfer from the original primary star to the secondary, have been left bound following the supernova explosion, and have not merged to form a TŻO (see text). Hatched regions indicate systems that have undergone stable mass transfer (+45°) and dynamically unstable mass transfer (–45°). The histogram that encloses the hatched region is the sum of the distributions for stable and unstable systems. A single Maxwellian kick distribution with $\sigma = 200\,\mathrm{km\,s^{-1}}$ has been applied to all NSs.

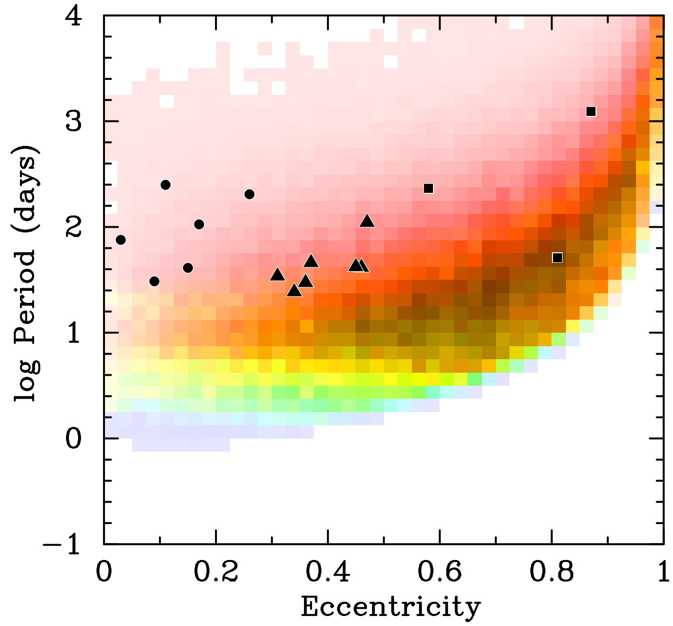

FIG. 3.— Two-dimensional distribution of orbital period and eccentricity for the systems in Fig. 2 with secondary masses $> 8\,M_\odot$. The intensity and color of a given square "pixel" indicate the total number of binaries and the stability of mass transfer, respectively. Pure red indicates only stable mass transfer, while pure blue indicates only dynamically unstable mass transfer. Colors that are not blue or red represent a mixture of stable and unstable systems; pure green indicates equal numbers. The intensity scale is linear and the lightest pixels represent $\sim 1\%$ of the number represented by the most intense pixel in the figure. Overlayed on the plot are markers that show the period and eccentricity (or upper limit) for the wide, low-eccentricity HMXBs (circles), the better-known eccentric HMXBs (triangles), and the long-period binary radio pulsars with massive companions (squares).

pulse-period variations (due to accretion torque noise), it can be difficult to measure their orbits very precisely.

4.3. *The Case for Small Kicks: Preliminary Arguments*

The most important factor in determining from model calculations the number of wide, low-eccentricity HMXBs in the Galaxy is the distribution in NS natal kick speeds. A kick speed that is comparable to the relative orbital speed prior to the SN is likely to yield a highly eccentric binary following the explosion, including the probable event that the binary is disrupted ($e > 1$). This statement is illustrated more quantitatively in Fig. 1, where we plot the probability that the post-SN eccentricity is < 0.2 for a $3\,M_\odot$ helium-star primary (NS progenitor) and a $12\,M_\odot$ secondary (typical pre-SN masses) with one of three pre-SN orbital periods, as a function of the kick speed, v_k. The distribution in kick directions was assumed to be isotropic. For all three initial orbital periods, the probability is $< 5\%$ when $v_k > 0.5\,v_{\rm orb}$, and the probability is $< 10\%$ when $v_k > 50\,\mathrm{km\,s^{-1}}$.

Hansen & Phinney (1997) found that a Maxwellian distribution in kick speeds, given by

$$p(v_k) = \sqrt{\frac{2}{\pi}}\frac{v_k^2}{\sigma^3}e^{-v_k^2/2\sigma^2} \ , \qquad (7)$$

is consistent with the data on pulsar proper motions, where the best fit was obtained with $\sigma \simeq 190\,\mathrm{km\,s^{-1}}$. A recent study by Arzoumanian, Chernoff, & Cordes (2001) utilized a two-component Maxwellian distribution, and found that 40% of their model pulsars were contained in the low-speed component with $\sigma \sim 90\,\mathrm{km\,s^{-1}}$, while the remaining pulsars populated the high-speed component with $\sigma \sim 500\,\mathrm{km\,s^{-1}}$. A single-component Maxwellian kick distribution predicts that $\sim 3\%$ of NSs are born with speeds $< 50\,\mathrm{km\,s^{-1}}$ for $\sigma = 100\,\mathrm{km\,s^{-1}}$, and $\sim 0.4\%$ for $\sigma = 200\,\mathrm{km\,s^{-1}}$. This information, combined with the results displayed in Fig. 1, illustrates that the conventional wisdom regarding NS kicks does not favorably produce wide binaries with low eccentricities. However, the statistical significance of the new class of HMXBs can only be quantitatively demonstrated by combining a complete population synthesis study with observational considerations regarding the discoverability of these systems.

4.4. *The Case for Small Kicks: Population Study*

Our population synthesis yields the fraction, F_0, of massive, primordial binaries that evolve into incipient HMXBs with orbital parameters in the range $P_{\rm orb} > 30\,\mathrm{d}$ and $e < 0.2$. An upper limit to the expected present total number of HMXBs in the Galaxy with properties similar to

those in Table 1 is obtained if we multiply F_0 by the Galactic formation rate of massive stars, $\sim 10^{-2}\,\mathrm{yr}^{-1}$ (the approximate Galactic rate of core-collapse supernovae; Cappellaro, Evans, & Turatto 1999), and the maximum lifetime of the HMXB phase, $\sim 10^7\,\mathrm{yr}$ (the approximate evolutionary timescale of the secondary). Therefore, the current total number of wide, low-eccentricity HMXBs in the Galaxy is expected to be $N_{\rm tot} < F_0 \times 10^5$.

Of course, only a fraction, $F_{\rm dis}$, of the $N_{\rm tot}$ HMXBs could have been discovered by X-ray satellites that have scanned and/or monitored the X-ray sky (e.g., *Uhuru*, *HEAO-1*, *RXTE*, *CGRO*). A simple way to estimate $F_{\rm dis}$ is to apply a flux limit, $S_{\rm min}$, that is appropriate for a particular satellite instrument. For a given X-ray luminosity, $L_{\rm X}$, the maximum distance at which the source could be detected is $d_{\rm max} = (L_{\rm X}/4\pi S_{\rm min})^{1/2}$. If we assume that HMXBs do not move very far from where they are formed, then an estimate of $F_{\rm dis}$ for a population of sources of luminosity $L_{\rm X}$ is just the probability that an O or B star is formed in a cylinder of radius $d_{\rm max}$ about the position of the Sun, perpendicular to the Galactic plane. Following Paczyński (1990) and Brandt & Podsiadlowski (1995), we adopt a disk distribution of stars given by

$$p(R) \propto R \exp(-R/R_0) \ , \tag{8}$$

where R is the Galactocentric radius and R_0 is the radial scalelength, taken to be 4.5 kpc (van der Kruit 1987).

The sensitivity with which the 2-10 keV X-ray sky has been probed for weak and transient HMXB systems is difficult to estimate. Some early scanning detectors aboard *Uhuru* and *HEAO-1* surveyed the sky for relatively brief periods (e.g., $\sim 1\,\mathrm{yr}$) with detection sensitivities as low as $S_{\rm min} \simeq 6 \times 10^{-11} \mathrm{ergs\,s^{-1}\,cm^{-2}}$. In more recent times, the *Ginga* and *RXTE* satellites have been used to conduct limited pointed surveys of small regions of the sky, searching for X-ray pulsations from HMXBs; such studies were sensitive down to $S_{\rm min} \simeq 3 \times 10^{-11} \mathrm{ergs\,s^{-1}\,cm^{-2}}$. However, the most sustained survey of the sky, with reasonable sensitivity, is that being conducted by the ASM aboard the *RXTE* satellite, which has been operating successfully for the past 5 years. It has sensitivities of $S_{\rm min} \simeq 3 \times 10^{-10} \mathrm{ergs\,s^{-1}\,cm^{-2}}$ for X-ray sources of known position, and $S_{\rm min} \simeq 2 \times 10^{-9} \mathrm{ergs\,s^{-1}\,cm^{-2}}$ for the detection of new sources (e.g., transients).

Sources of steady luminosity comparable to that of X Per and/or γ Cas (i.e., $\sim 10^{35}\,\mathrm{ergs\,s^{-1}}$) would likely have been detected in previous surveys of the sky out to distances of $\sim 3\,\mathrm{kpc}$. However, objects that are transient in nature, with only infrequent "on" states at these low luminosities, might be detected with the ASM only out to distances of $\sim 600\,\mathrm{pc}$. Thus, the fractional effective volume of our Galaxy (from eq. [8]) that has been well studied for wide, low-luminosity HMXBs probably lies in the range of $\sim 10^{-4} - 5 \times 10^{-3}$. This is the range of values that we then consider for our parameter $F_{\rm dis}$. Of course, if transient X-ray sources flare up to much higher luminosities, then the discovery probability at larger distances can go up dramatically.

Some results of our population study are shown in Figs. 2 and 3, where we have adopted a Maxwellian kick distribution with $\sigma = 200\,\mathrm{km\,s^{-1}}$ and the standard-model parameters given in § 3. It is apparent from Figs. 2 and 3 that binaries containing a massive secondary and that have low eccentricities and long periods are not produced favorably. These simulations yield $F_0 \sim 4 \times 10^{-4}$, which corresponds to at most ~ 40 wide, nearly circular HMXBs in the Galaxy. It is not at all reasonable to suspect that we have already detected and precisely measured the orbits of $\sim 15\%$ (i.e., 6 of 40) of this inconspicuous population, over the entire Galaxy. For a reduced value of $\sigma = 100\,\mathrm{km\,s^{-1}}$, we find that F_0 is increased by roughly a factor of five, and so perhaps as many as 200 such objects are present in the Galaxy. This again is probably too small a number, considering that the assumed detectable lifetime of $10^7\,\mathrm{yr}$ is likely to be an upper limit, and that the efficiency for discovery, $F_{\rm dis}$, must be quite low.

A Maxwellian kick distribution with $\sigma \sim 100\,\mathrm{km\,s^{-1}}$, applied uniformly to *all* NSs, may be consistent with the speeds of a large fraction of isolated pulsars with measured proper motions (Arzoumanian, Chernoff, & Cordes 2001), but conflicts arise when we consider significantly smaller values. The kinematics of the populations of single pulsars and LMXBs do suggest a large mean kick speed (e.g., Hansen & Phinney 1997; Brandt & Podsiadlowski 1995; Johnston 1996), and a Maxwellian distribution with $\sigma \gtrsim 100\,\mathrm{km\,s^{-1}}$ seems to reproduce the properties of these populations reasonably well. However, based upon our discussion above, we suggest that there are many wide, nearly circular HMXBs in the Galaxy (possibly well in excess of 1000), and that the NSs in these systems require fairly small kicks ($v_k \lesssim 50\,\mathrm{km\,s^{-1}}$) on average[2]. The apparent conflict with the other known NS populations is resolved if the mean kick speed depends on the evolutionary history of the NS progenitor in a binary system. We now go on to describe this scenario in the next two sections.

5. AN EVOLUTIONARY MODEL

With some perspective, we can motivate a phenomenological picture that accounts for the new population of long-period, low-eccentricity HMXBs, and which is consistent with what we know about the Galactic NS populations. There are four basic constraints that our model must satisfy. First, the orbits of the systems listed in Table 1 suggest that they did not experience a dynamical spiral-in phase prior to the first SN, and that the NSs in these binaries did not receive a very large kick. We propose that a significant fraction of those NSs whose progenitors underwent case B_e or C_e mass transfer received natal kick speeds of $\lesssim 50\,\mathrm{km\,s^{-1}}$. Second, the orbits of all other binaries containing a NS and a massive stellar companion should be naturally accounted for. Such binaries include short-period HMXBs and moderately wide, eccentric HMXBs (see § 2), as well as the three long-period binary radio pulsars with massive companions (PSR B1259–63, PSR J1740–3052, and J0045–7319; Johnston et al. 1992; Kaspi et al. 1994; Manchester et al. 1995; Kaspi et al. 1996; Stairs et al. 2001). Third, the model should be able to approximately reproduce the numbers and properties of luminous low-mass X-ray binaries in the Galaxy. Fourth, our basic picture should also be consistent with the observed kinematical distribution of isolated pulsars in the Galaxy, on which the NS kick distributions are based.

[2] Note that the mean of a Maxwellian distribution is given by $(8/\pi)^{1/2}\sigma$.

The orbits of the observed short-period HMXBs have been affected by tidal interactions (see § 4), and so tell us very little about the NS kick. HMXBs with orbital parameters of $P_{\rm orb} \sim 20 - 100\,{\rm d}$ and $e \sim 0.3 - 0.5$, in addition to the long-period, binary radio pulsars are somewhat difficult to interpret definitively, since they are consistent a priori with being the products of either stable or dynamically unstable mass transfer. This is indicated in Fig. 2 by the overlap of the period distributions for the stable and unstable systems. If these binaries have experienced a dynamical spiral-in, then their survival (as opposed to merger) essentially requires that the mass transfer was case B_l or C_l (see § 3), and our model predicts that the NSs received the conventional large kicks. If the mass transfer was stable (case B_e or C_e), then a significant eccentricity is still possible as long as the magnitude of the kick is an appreciable fraction of the pre-SN orbital speed. This point is important, and it is worthwhile to discuss a particular example.

Consider the very long-period, highly eccentric binary pulsar PSR B1259–63 with $P_{\rm orb} = 1236.72\,{\rm d}$ and $e = 0.87$. The orbital separation at periastron is $\sim 140\,R_\odot$, for an assumed mass of $10\,M_\odot$ for the secondary. This is the smallest circular pre-SN orbit that is permitted (e.g., Flannery & van den Heuvel 1975), and so the largest pre-SN relative orbital speed is $v_{\rm orb} \sim 130 - 170\,{\rm km\,s^{-1}}$, for a reasonable range in pre-collapse core masses. If the fractional mass lost in the SN explosion is small, then a post-SN eccentricity of order unity is possible for a kick speed that is $\lesssim 40\%$ of the orbital speed, or $\lesssim 70\,{\rm km\,s^{-1}}$ for PSR B1259–63 (e.g., Brandt & Podsiadlowski 1995; Appendix A of PRP); in an absolute sense, this is not a very large kick.

The latter two semi-empirical constraints on our model are satisfied if we suppose that a NS receives the usual large kick if its progenitor is allowed to evolve into a red supergiant (i.e., a single progenitor or case B_l, C_l, or D for a binary system). Within this framework, isolated, fast-moving pulsars are likely to have come from single progenitors or wide binaries that were disrupted by the SN explosion. Also, by our hypothesis, the NSs born in LMXBs would receive kicks drawn from a conventional distribution, since their standard formation channel involves a common-envelope phase in the case B_l or C_l scenario (e.g., Bhattacharya & van den Heuvel 1991; Kalogera & Webbink 1998).

We have redone our population synthesis calculation with the following simple modification. If the mass transfer is case B_e or C_e (see § 3), the NS kick is chosen from a Maxwellian distribution with $\sigma = 20\,{\rm km\,s^{-1}}$, a small but otherwise arbitrary value. On the other hand, if the mass transfer begins while the primary is a red supergiant (case B_l, C_l), or there is no mass transfer (case D), we adopt a more conventional kick distribution, with $\sigma = 200\,{\rm km\,s^{-1}}$. Rather than applying the same kick distribution to *all* case B_e and C_e systems, we could have focused our attention on only the stable case B_e and C_e systems, since these are the alleged progenitors of the new class of HMXBs. However, our choice of treating all case B_e and C_e binaries on an equal footing is partly motivated by a theoretical model, which we discuss in the next section.

Figures 4 and 5 should be compared to Figs. 2 and 3, respectively. Many more systems with long periods and low eccentricities are produced when $\sigma = 20\,{\rm km\,s^{-1}}$ is adopted for the case B_e and C_e systems. This simulation yields $F_0 \sim 2.6 \times 10^{-2}$ and a present Galactic population of $\lesssim 2600$ wide, low-eccentricity HMXBs, a factor of 65 more than in the case where $\sigma = 200\,{\rm km\,s^{-1}}$ is applied to all NSs. If such a large population of long-period HMXBs is indeed present in the Galaxy, their integrated X-ray luminosity cannot exceed $\sim 10^{38}\,{\rm ergs\,s^{-1}}$, the total X-ray luminosity of the so-called "Galactic ridge" of unresolved X-ray sources (e.g., Yamasaki et al. 1997; Valinia & Marshall 1998; Valinia, Kinzer, & Marshall 2000). This is not problematic if these HMXBs typically have persistent X-ray luminosities of $\lesssim 10^{35}\,{\rm ergs\,s^{-1}}$.

We have also calculated the production efficiency for systems that may evolve to resemble the HMXBs with moderate-to-long periods and significant eccentricities (triangles in Figs. 3 and 5), as well as for systems similar to the massive, long-period, highly eccentric, binary radio pulsars (squares in Figs. 3 and 5). In our code, we simply defined the HMXBs by the parameter ranges of $20\,{\rm d} < P_{\rm orb} < 100\,{\rm d}$ and $0.3 < e < 0.5$, and the binary radio pulsars by $100\,{\rm d} < P_{\rm orb} < 1000\,{\rm d}$ and $0.5 < e < 0.9$. Furthermore, we define the formation efficiency as the fraction of primordial binaries that ultimately evolve into the systems of interest (the parameter F_0 for the new class of HMXBs). If we apply the conventional kick scenario, with $\sigma = 200\,{\rm km\,s^{-1}}$ for all NSs, the formation efficiencies are $\sim 0.4\%$ for both the eccentric HMXBs and binary radio pulsars. On ther other hand, in our modified kick scenario described above, the formation efficiency for the eccentric HMXBs is $\sim 1.7\%$, while for the binary radio pulsars the efficiency is $\sim 1.3\%$. The increase in the number of systems is certainly substantial, but not nearly as dramatic as the increase in the number of long-period, low-eccentricity HMXBs.

6. A PHYSICAL MODEL

The simple scenario we have outlined above is purely phenomenological. If the picture is essentially correct, then we should ask: What physical process(es) may account for the dependence of the NS kick on the evolutionary history of its progenitor in a binary system? We suggest that the rotation of the collapsing core plays a crucial role in determining the magnitude of the NS kick, and that there is a natural reason to expect a possibly sharp break in the distribution of rotation rates of stellar cores exposed following mass transfer.

Many young, isolated, massive stars are observed to rotate at $\sim 20 - 50\%$ of their breakup rates (e.g., Fukuda 1982; Howarth et al. 1997). For a main-sequence star of mass $10\,M_\odot$, the breakup angular frequency is $\Omega_b \sim 10^{-4}\,{\rm rad\,s^{-1}}$. If the stellar core initially has the same angular velocity, and the core retains a constant angular momentum as it evolves, then the NS that is produced is expected to rotate close to its breakup rate (i.e., with a period of $\lesssim 1\,{\rm ms}$). However, the question of exactly how such rapid rotation on the main sequence translates to the rotation of the pre-collapse iron core, immediately prior to NS formation, is difficult to answer, owing to the large number and complexity of hydrodynamical and magnetohydrodynamical angular-momentum transport processes.

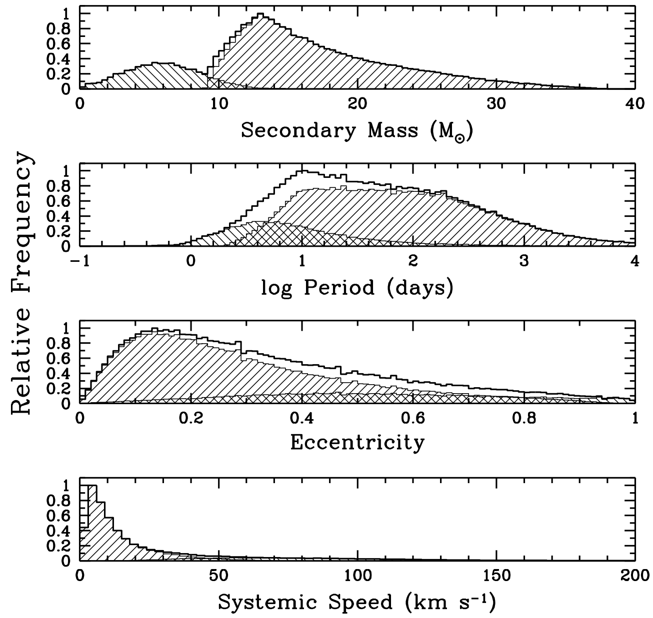

FIG. 4.— Same as Fig. 2, but with $\sigma = 20\,\mathrm{km\,s^{-1}}$ applied to the NSs born in all case B_e and C_e binaries, and $\sigma = 200$ applied to all other NSs. Note that the eccentricity distribution for the stable systems has a distinct peak at $e \sim 0.15$.

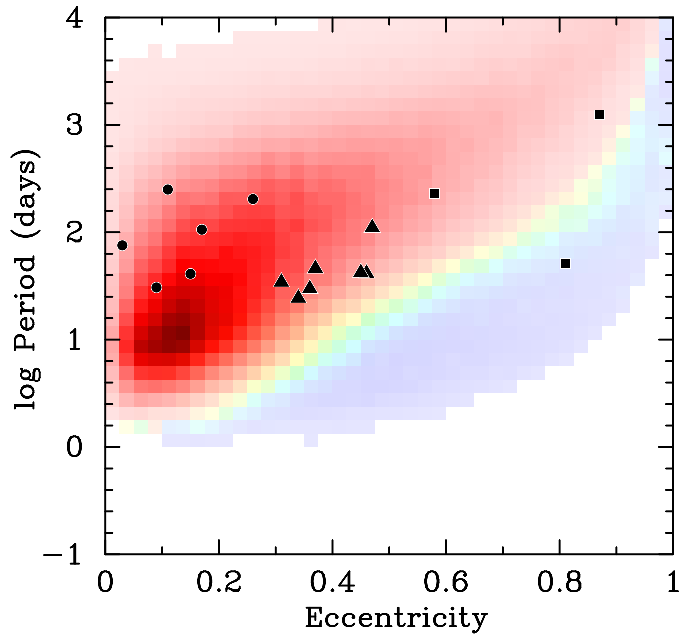

FIG. 5.— Distribution of orbital period and eccentricity for the systems in Fig. 4 with secondary masses $> 8\,M_\odot$. A value of $\sigma = 20\,\mathrm{km\,s^{-1}}$ applied to the NSs born in all case B_e and C_e binaries, and $\sigma = 200$ applied to all other NSs. The colors, intensities, and symbols have the same meaning as in 3.

Heger, Langer, & Woosley (2000; hereafter, HLW) have conducted the most sophisticated and detailed study to-date of isolated, rotating, massive stars, which included treatments of various hydrodynamical instabilities, but neglected the influence of magnetic fields. Interestingly, they found that the angular momentum of the pre-collapse core was quite insensitive to the initial rotation rate of the star, and that the nascent NS remnant would spin at close to its breakup rate, although their simulations could not follow the evolution beyond the start of core collapse.

In the binary systems we are considering, the first phase of mass transfer is expected to strip the hydrogen-rich envelope from the primary (see § 3), thus exposing its core. The results of HLW suggest that this core will be a fairly rapid rotator if the primary was initially rapidly rotating. Furthermore, the results of HLW indicate that the angular momentum of the exposed core should not depend strongly on the evolutionary state of the primary at the onset of mass transfer, if only hydrodynamical angular-momentum transport processes are considered. However, magnetic fields may introduce just such a dependence.

In the presence of differential rotation, an initially poloidal magnetic field will be wound up into a predominantly azimuthal field, where the magnitude of the azimuthal component is proportional to the number of differential turns (for a review of this and related magnetohydrodynamic processes in stars, see Spruit 1999). If this generation and amplification of the magnetic field occurs between the surface of the convective core and the outlying stellar envelope of a massive star, then the resulting magnetic torque will cause the core to spin down. The torque is transmitted by the r-ϕ component, $B_r B_\phi/4\pi$, of the Maxwell stress tensor. Suppose that the core of mass M_c is initially rotating with an angular velocity, Ω_c, and that the stellar envelope is nonrotating. The timescale for the core to spin down, τ_s, is approximately (see Spruit 1998)

$$\tau_s \sim \frac{I_c \Omega_c}{r_c^3 \bar{B}^2} \sim 10\,\mathrm{Gyr}\left(\frac{k}{0.1}\right)\left(\frac{M_c}{M_\odot}\right) \times \left(\frac{\Omega_c}{10^{-4}\,\mathrm{s^{-1}}}\right)\left(\frac{\bar{B}}{1\,\mathrm{G}}\right)^{-2}, \quad (9)$$

where $I_c = kM_c R_c^2$ is the moment of inertia of the core and $\bar{B} = (B_r B_\phi)^{1/2}$. The geometric mean field $\bar{B}$ appearing in eq. (9) increases with time, because of the winding-up of the B_r component. The 1 G field used for scaling in eq. (9) is quite small as compared with field strength that can, in principle, be reached as a result of the amplification process. It is thus possible for the coupling timescale τ_s to be shorter than the evolutionary timescale of the star.

Immediately following the depletion of hydrogen in the core, a massive star expands to giant dimensions on a thermal timescale ($\sim 10^4 - 10^5$ yr). Significant differential rotation between the core and the envelope will only be established after the star crosses the Hertzsprung gap and develops a deep convective envelope. It is thus reasonable to suggest that magnetic torques should not be very effective in spinning down the core during this short-lived evolutionary phase, and that a helium star should be rapidly rotating if it is uncovered following case B_e or C_e mass transfer.

If mass transfer takes place at a later stage of evolution (i.e., during the first giant branch or asymptotic giant branch), the stellar core may rotate millions of times with respect to the very slowly rotating convective envelope. One might take the view (Spruit & Phinney 1998) that under these circumstances there is plenty of time for

a strong toroidal magnetic field to build up. The consequence of this would be that the cores of evolved stars would approach corotation with their envelopes, and their angular momentum would then be so small that the NSs formed will have spin periods of hundreds of seconds. This is problematic, since the spin of observed young NS are tens of milliseconds in several cases (e.g., the Crab pulsar has a period of 33 ms). Spruit & Phinney (1998) resolved this dilemma by attributing the current, short spin periods to off-center kicks.

In reality, the magnitude of the geometric mean field $\bar{B}$ that can actually be obtained in a differentially rotating star is not just a matter of simple winding-up of field lines. The approximately azimuthal fields that develop from differential rotation are known to be prone to instabilities (Tayler 1973; Acheson 1978). These instabilities may limit the attainable field strengths (for a discussion, see Spruit 1999). On the other hand, the unstable fluid displacements would create new poloidal field components which in turn would be wound up to generate more azimuthal field. It is thus possible that an unstable azimuthal field will develop into a *dynamo process* operating on the differential rotation. In Spruit (2001) an estimate is developed for the behavior of such a dynamo process and the $\bar{B}$ it produces. Preliminary calculations of the evolution of rotating stars that incorporate this formalism (Heger, Woosley, & Spruit, in preparation) indicate that the coupling between cores and envelopes could be less efficient than assumed in Spruit & Phinney (1998).

Based upon the physical arguments presented above, and the phenomenological picture discussed in § 5, we suggest that rapidly rotating stellar cores exposed following stable case B_e or C_e mass transfer produce NSs with small natal kicks, while NSs formed at a later stage of evolution (case B_l, C_l, or D), where the pre-collapse cores may be spinning quite slowly, receive the conventional large kicks. The collapse of a rapidly rotating core is certainly more dynamically complex than the collapse of a core that is initially nonrotating. However, it is not obvious a priori whether a rapidly or slowly spinning pre-collapse core should ultimately yield a larger average natal kick to the NS, since the physical mechanisms that may be responsible for the kick are poorly understood. One possibility is that rapid rotation has the effect of averaging out the asymmetries that give rise to large NS kicks (Spruit & Phinney 1998).

7. FURTHER IMPLICATIONS OF THE MODEL

7.1. *Neutron Star Retention in Globular Clusters*

It is apparent that globular clusters must contain appreciable numbers of NSs. For example, 22 millisecond radio pulsars have been detected in the massive globular cluster 47 Tuc, and many more are thought to be present (Camilo et al. 2000; see also PRP and references therein). This abundance of NSs raises an interesting question. If NSs are born with speeds that are typically in excess of $100-200\,\mathrm{km\,s^{-1}}$, how is it that even a very dense globular cluster, with a central escape speed of $\sim 50\,\mathrm{km\,s^{-1}}$, can retain so many? A conventional Maxwellian kick distribution, with $\sigma = 200\,\mathrm{km\,s^{-1}}$ applied to all NSs, predicts that only $\sim 0.4\%$ of NSs are born with speeds $< 50\,\mathrm{km\,s^{-1}}$, and $\sim 3\%$ with speeds $< 100\,\mathrm{km\,s^{-1}}$. In PRP, we considered the influence of massive binary systems on the NS retention fraction. Our standard model calculation showed that $\lesssim 5\%$ of NSs born in binary systems could be retained in a typical cluster.

This long-standing *retention problem* is clearly alleviated if there exists a population of NSs that are born with kick speeds $\lesssim 50\,\mathrm{km\,s^{-1}}$, which is seemingly at odds with the large speeds inferred for isolated pulsars in the Galactic disk. The scenario that we have proposed in § 5 to account for the long orbital periods and low eccentricities of the HMXBs listed in Table 1 is not in conflict with the speeds of the isolated pulsars, by construction. Our hypothesis is that low-kick NSs are preferentially born in certain binary systems, and thus these NSs are much more likely to remain bound to their companions following the SN. If the secondary is massive, possibly as a result of accretion, the effect of the impulsive kick on a bound post-SN binary is diluted considerably, thereby allowing the binary to be retained in the cluster. Our simulations indicate that the NS retention fraction may be increased by more than a factor of four (to $\gtrsim 20\%$) if we adopt the phenomenological picture outlined in § 5 (see PRP for further details).

7.2. *Formation of Double Neutron Star Binaries*

A double NS (DNS) — a binary comprised of two NSs — seems like an improbable object; however, five proposed DNSs have been detected in the Galaxy. In all cases, only one of the components of the DNS is detected as a radio pulsar, and the other component is inferred to be a NS based on the mass function. The DNS in the globular cluster M15, PSR 2127+11C, probably formed dynamically (e.g., Phinney & Sigurdsson 1991), rather than from a massive primordial binary. The present discussion is restricted to the formation of DNSs in the Galactic disk, where the dynamical formation of binaries does not occur with any significant probability.

At the end of § 3, we very briefly described the standard formation scenario for DNSs in the Galactic disk (see, e.g., Bhattacharya & van den Heuvel 1991 for a more detailed discussion). We stated that the envelope of the secondary can only be successfully ejected by the first-formed NS if the orbit is sufficiently wide ($P_{\rm orb} \gtrsim 100\,\mathrm{d}$) at the time the secondary fills its Roche lobe. Therefore, the episode of mass transfer before the first SN must have been stable for the majority of binaries that ultimately evolve into DNSs. Our phenomenological picture for the formation of wide, low-eccentricity HMXBs involves relatively low kick speeds applied to NSs born in binary systems that have undergone case B_e or C_e mass transfer. For about half of the case B_e and C_e binaries (for $q_{\rm crit} = 0.5$; see § 3) the mass transfer is stable. Thus, our model may result in a dramatically increased formation efficiency for DNS progenitors, since many more wide binaries remain bound following the first SN than if the conventional large kicks are applied to all NSs.

We investigated the formation of DNSs with the following straightforward extensions to our population synthesis code. If the binary survives the first episode of mass transfer and the first SN without merging and without being disrupted, then we consider the eccentric post-SN orbit of the first-formed NS and the secondary. We suppose that once the secondary evolves to fill its Roche lobe, the orbit

quickly circularizes. Because of the extreme mass ratio, the subsequent phase of mass transfer is guaranteed to be dynamically unstable, and the orbital separation following the spiral-in is computed using eq. (4). If the new separation indicates that the radius of the hydrogen-exhausted core of the secondary exceeds its Roche lobe radius, then we assume a coalescence is the result. Finally, the new orbital parameters are computed following the SN explosion of the secondary's core, where the kick to the second-formed NS is drawn from a Maxwellian distribution.

It is interesting to note that, for the preferred progenitors of DNSs, the first episode of mass transfer was stable, in which case the secondary has accreted a considerable amount of mass and angular momentum. As a result, these secondaries should be rotating rapidly following mass transfer. This seems to be borne out by observations of HMXBs, where many systems contain a Be optical counterpart; the Be phenomenon is likely a consequence of rapid rotation (e.g., Slettebak 1988). Therefore, it seems as though we may apply a kick to the second NS in precisely the same way as for the first, with a value of σ that depends on the evolutionary state of the secondary when it fills its Roche lobe. This turns out *not* to be very important, however, since the mass loss from the exploding core of the secondary typically has a more disruptive influence on the orbit than the kick.

As a point of reference, we applied the more-or-less standard Maxwellian kick distribution, with $\sigma = 200\,\mathrm{km\,s^{-1}}$, to all NSs, both first- and second-formed. We find that the fraction of primordial binaries that successfully evolve into DNSs is $\sim 10^{-3}$. For a core-collapse SN rate of $10^{-2}\,\mathrm{yr^{-1}}$, this fraction corresponds to an approximate DNS birthrate of $\sim 10^{-5}\,\mathrm{yr^{-1}}$, consistent with other recent theoretical calculations that used similar methods and assumptions (e.g., Lipunov, Postnov, & Prokhorov 1997; Portegies Zwart & Yungelson 1998).

If we assume that NSs born following case B_e or C_e mass transfer receive kicks drawn from a Maxwellian with $\sigma = 20\,\mathrm{km\,s^{-1}}$, we find that the DNS birthrate is increased by roughly a factor of twenty, to $\sim 2 \times 10^{-4}\,\mathrm{yr^{-1}}$. This order-of-magnitude increase is almost entirely accounted for by the increase in the number of viable DNS progenitors — systems where the common-envelope is successfully ejected during the dynamical mass transfer episode from the secondary to the first-formed NS.

8. SUMMARY

Using a combination of observational and theoretical arguments, we have considered the significance of a new observed class of HMXBs, with orbits that are distinguished by relatively long periods ($P_{\mathrm{orb}} \sim 30 - 250\,\mathrm{d}$) and low eccentricities ($e \lesssim 0.2$). Our analysis indicates that the conventional wisdom regarding NS kicks does not adequately account for the number of these systems known at present, which comprise roughly 30% of HMXBs with measured orbital parameters. Members of this new class of HMXBs contain NSs that almost certainly received a fairly small kick ($\lesssim 50\,\mathrm{km\,s^{-1}}$) at the time of formation. A prevalence of such low-kick NSs is simply incompatible with large mean natal kick speeds ($\gtrsim 200 - 300\,\mathrm{km\,s^{-1}}$) inferred for isolated radio pulsars in the Galaxy. However, we have developed a phenomenological model that simultaneously accounts for the long-period, low-eccentricity HMXBs and which does not violate any previous notions regarding the kinematics of other NS populations (i.e., radio pulsars, LMXBs, and other HMXBs).

Specifically, we propose that a NS receives a relatively small kick if its progenitor star experienced case B_e or C_e mass transfer in a binary system. In operational terms, we utilized a Maxwellian distribution in kick speeds, but with a somewhat arbitrarily selected low value of $\sigma = 20\,\mathrm{km\,s^{-1}}$ applied to NSs born in case B_e or C_e binaries, and for all other NSs (case B_l, C_l, or D binaries, as well as isolated progenitors) we adopted a much higher value of $\sigma = 200\,\mathrm{km\,s^{-1}}$. This scenario results in sufficient numbers for the new class of HMXBs, and, by construction, is consistent with the numbers and properties of other NS populations in the Galaxy.

If this phenomenological picture is basically correct, then there must be some physical explanation for why the magnitude of the kick depends on the evolutionary history of the NS progenitor. We suggest that the rotation of the pre-collapse core of a massive star introduces just such a dependence. If the hydrogen-exhausted core of an initially rapidly rotating massive star is exposed following case B_e or C_e mass transfer in a binary, then the core is also likely to be a rapid rotator, as implied by the work of Heger, Langer, & Woosley (2000). On the other hand, if the NS progenitor is allowed to evolve into a red supergiant (case B_l, C_l, D, or a single star), then significant magnetic torques, amplified by the strong differential rotation between the core and the deep convective envelope (Spruit & Phinney 1998; Spruit 1999), may cause the core to spin down dramatically. Thus, for whatever reason, the dynamics of core collapse may be such that low kick speeds result for rapidly rotating pre-collapse cores, and cores that are spinning slowly preferentially yield the conventional large kick speeds.

Our model to explain the new class of HMXBs requires that a large fraction of NSs born in binary systems receive only a small recoil speed following core collapse and the SN explosion. This simple requirement has important implications for at least two very different problems. First, the problem of retaining NSs in globular clusters is alleviated if not solved if our hypothesis is correct. Second, our scenario predicts an order of magnitude larger birthrate of double NS binaries than if the conventional kick distributions are applied.

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